

Optical Injection Locking Techniques for Performance Improvement in Analog mm-Wave Systems

Ahmed Abdellatif¹ and Zoran Vujicic¹

¹Instituto de Telecomunicações, Campus Universitario De Santiago, 3810-193 Aveiro, Portugal

Tel: (351) 937 035140, e-mail: ahmedabdellatif@av.it.pt

ABSTRACT

We report a state-of-the-art survey on the applications of optical injection locking in analog mm-Wave systems. An overview of recent implementations towards a cost effective generation of high purity mm-Wave signals, and in overcoming typical system impairments encountered in analog radio over fiber architectures, is presented.

Keywords: Analog Systems, Millimetre Wave Communication, Optical Injection Locking

1. INTRODUCTION

mm-Wave (MMW) transmission is pursued to unlock unlicensed spectrum opportunities, where high cell densification is required to counteract the limited wireless propagation range [1]. To satisfy the capacity, latency, and signal fidelity requirements, optical fiber transport technologies are considered as fronthauling options. As one of the main candidate architectures, analog-radio-over-fiber (ARoF) handles capacity requirements with higher spectral efficiency compared to its counterparts, but may struggle to maintain signal fidelity over longer fiber spans and or high bandwidth/MMW frequency operation [2]. The main reasons behind this issue are high sensitivity to the intrinsic imperfections of opto-electronic components related to amplitude and phase noise and modulation nonlinearity, as well as the carrier fading effect caused by fiber dispersion [3]. As an optical frequency and phase synchronization technique, Optical Injection Locking (OIL) is of particular interest in high MMW ARoF systems, as it enables laser linewidth and bandwidth enhancement, as well as relative intensity noise and chirp reduction [4]. We hereby outline recent state-of-the-art (SOTA) implementations of OIL for system performance improvement towards the feasibility of high-end MMW ARoF systems. We focus on OIL features relevant to typical performance impairments in such systems: the noise and linewidth enhancement in MMW tones generation and selection, the modulation bandwidth enhancement of directly modulated lasers (DML), and the enhancement of chromatic dispersion (CD) tolerance through OIL-based Optical Single Sideband (OSSB) generation.

2. OPTICAL TONES GENERATION AND DEMULTIPLEXING

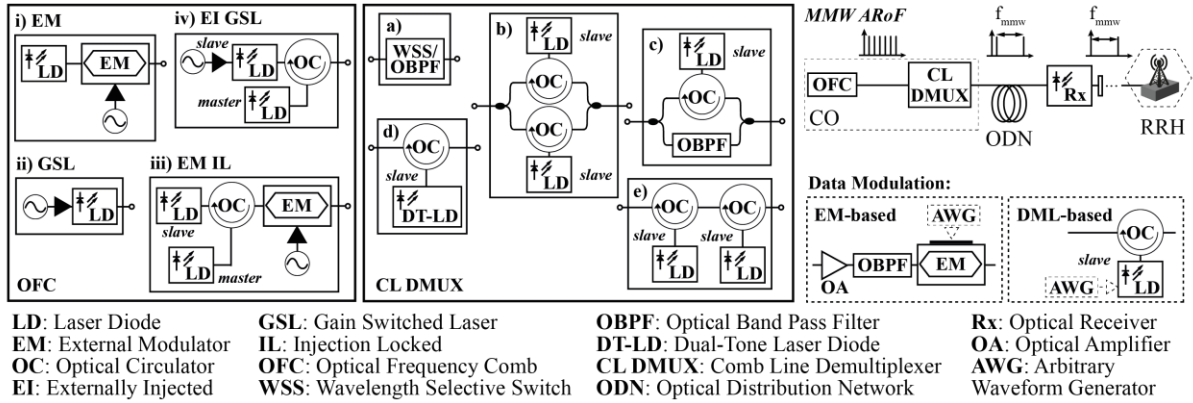


Fig 1. OFC generation and DMUX architectures based on IL for MMW ARoF systems. The right-top inset shows general ARoF architecture based on remotely-seeded coherent heterodyne detection. The left and middle insets summarize the OFC and CL DMUX architectures from recent literature, respectively, while the right-bottom inset showcases the configurations used for data modulation. In case that signal modulation is applied at the OFC stage, the CL DMUX stage may be distributed to the RRH [13].

Typical ARoF systems depicted in Fig.1 involve remotely seeded optical heterodyning (OHD), whereby an optical carrier (*i.e.*, tone), serving as a local oscillator for self-seeded up-conversion, is transmitted along with the data-modulated carrier from the Central Office (CO) to the Remote Radio Head (RRH). The optical tones are spaced by the final, air-interface MMW frequency, to enable the replacement of high frequency electronic components with the high bandwidth optical components at the RRH. Although the most straight forward implementation approach in such systems is based on the use of un-correlated laser sources (*i.e.*, dual-laser architectures), it typically results in prohibitive phase noise degradation requiring DSP along with additional Analog-to-Digital and Digital-to-Analog (ADC/DAC) components at the RRH, offsetting the cost benefits of

ARoF. To avoid poor spectral purity and phase noise of MMW tones generated using dual-mode lasers or dual-laser architectures, as well as the lack of tunability feature of tones generated using mode-locked lasers, ARoF systems often rely on optical frequency comb (OFC) generators for coherent OHD [5], [6].

An OFC may be realized by using an ‘off-the-shelf’ Laser Diode (LD), such as Distributed Feedback (DFB) laser, which is typically either used to seed an External Modulator (EM) [8]-[12], or is gain switched to produce correlated optical tones with tunable frequency spacing [12]-[15]. Block-diagrams for considered EM-based OFCs are shown as options i) and iii), whereas Gain Switched Laser (GSL)-based OFCs are presented as options ii) and iv) in Fig.1. Although other techniques may be considered for OFC generation, in line with recent demonstrations we hereby focus on the elementary EM- and GSL-based implementations and their counterparts relying on IL for improved performance, depicted as iii) and iv) in Fig.1, respectively. Namely, the consideration of IL within the OFC generation element is pursued towards addressing the comb noise and linewidth requirements. Compared to the standard GSL OFC (option ii) in Fig.1), Externally Injection locked (EI)-GSL OFCs enable significant improvements in both optical carrier-to-noise ratio and linewidth, and may be considered for applications requiring the OFC linewidth within the order of kHz [15]. The ability to control the separation between the OFC tones is an important feature as well, as it allows the frequency tuning of the generated MMW RF carrier.

In recent years, OIL has also become a key feature in the implementation of Comb Line Demultiplexing (CL DMUX), depicted in the middle inset of Fig. 1. CL DMUX is required to separate the desired OFC tones (*i.e.*, tones spectrally spaced by the desired MMW frequency) prior to data modulation and fiber transmission. As shown Fig. 1, the recent SOTA implementations may be grouped into two main categories. The most commonly used approach is strictly based on optical filtering (Fig.1a), relying on tunable Optical Band Pass Filters (OBPF), Wavelength Selective Switches (WSS) or Arrayed Waveguide Gratings (AWG) [8], [12], [13]. Since the output power of OFCs, including those based on the EL-GSLs, is typically severely limited, this approach necessitates the use of optical amplification which degrades the Optical Signal-to-Noise Ratio (OSNR). An alternative approach, gaining significant traction in recent years, involves laser-based active DMUX relying on OIL (Fig.1b-e). The application of OIL allows the output of each DMUX arm to inherit the frequency and phase characteristics of the OFC and enables high Comb Line Suppression Ratio (CLSR) [16], resulting in the amplification of two highly correlated tones separated by the desired MMW frequency. Thus, the tone selection based on active DMUX, a technique enabling simultaneous filtering and amplification while avoiding Amplified Spontaneous Emission (ASE) noise, was proposed as an alternative to the techniques based on passive optical filtering and optical amplification [14]. It is of note that, although optical filtering may still be used for OSSB generation and/or OSNR improvement following the OIL stage [11], [13], [14], it is not a requirement for tone DMUX functionality. Hybrid options, partially relying on tunable OBPF, and active OIL-based DMUX applied to a single arm, are also considered [13].

In dual-arm implementations of OIL-based DMUX, shown in Fig.1b and c, phase de-correlation between the two optical tones is induced by path length differences and chromatic dispersion, and often requires pre-compensation using a tunable Optical Delay Line (ODL) [12]. An interesting alternative is presented in Fig.1e, where a serialized dual-stage active DMUX scheme based on OIL is used to alleviate the need for optical path length matching and thus mitigate the increased linewidth sensitivity caused by phase walk-off [15]. Therefore, compared to the dual-arm configuration, the application of dual-stage OIL-based DMUX enables the use of low-cost OFCs with linewidth of the order of MHz [15]. It also enables simplified architecture not requiring splitters, tunable ODLs, optical amplifiers, or EMs when one of the slave lasers is directly modulated (DML). Compared to the DT LD based solutions (Fig.1d), this approach enables higher degree of control over the individual DMUX stages, as well as a typically higher MMW frequency stability [9], [10]. Tuning stability is another system aspect improved by means of OIL, however, the CL DMUX solutions relying on dual-laser Photonic Integrated Circuits (PIC) may still exhibit frequency drift at high MMW frequencies related to the thermal control. Independent thermal control for each laser on the chip may yield optimal stability at the cost of increased complexity, while the alternative may be limiting the MMW tunability range [10].

A summary of the aforementioned techniques and considered recent works is reported in Table I. The lack of reported transmission ODN length indicates back-to-back experimental implementations, while the absence of wireless transmission length indicates the lack of wireless transmission. Table I shows that, while the MMW generation and the fiber transport have been studied in end-to-end optical links, including efforts to also enable sub-THz bands [10], the wireless channel transmission is still often entirely omitted. As shown in Fig. 1, data modulation is typically considered either by using the EM-based configuration applied after the CL DMUX stage, or by using the DML and IL-based configuration integrated within the OFC or CL DMUX elements. The former is typically implemented using the optical amplification and filtering for OFC and EM loss compensation, while the IL-based configuration clearly enables simplified system architecture. It is also of note that even when relying on high bandwidth photo detection (PD), transmission capacity and/or reach in high MMW frequency regimes may still be a limiting factor in ARoF. Nevertheless, the main focus of all considered

works is on showcasing the improvements in MMW signal phase noise mitigation due to the use of OIL, towards OFC and CL DMUX based channel (de-) aggregation.

Table 1. Recent implementations of OFC generation and DMUX based on IL for MMW ARoF, in relation to the schemes shown in Fig.1.

Year/ Ref.	f_{MMW} (GHz)	Fig.1	Data Modulation		Reach, ODN/ Wireless
			Type	Rate/Format	
2021 [7]	28	iii-a	EM-based after DMUX	2Gb/s QPSK	- / 4m
2022 [13]	35	iv-c	IL DML-based at OFC	1.17Gb/s 64QAM	10km / -
2022 [15]	37.5	ii-e	IL DML-based at DMUX	1.32Gb/s 64QAM	25km / -
2018 [12]	52.8	iv-a	EM-based after DMUX	4.5Gb/s 64QAM	25km / -
2020 [14]	60	iv-b	IL DML-based at DMUX	0.89Gb/s 64QAM	25km / -
2022 [9]	60	i-d	EM-based after DMUX	1Gb/s QPSK	25km / -
2018 [11]	80	i-a	IL DML-based after DMUX	28Gb/s PAM4	- / -
2022 [10]	93	i-b	EM-based after DMUX	12.5Gb/s OOK	- / 65cm

3. MODULATION BANDWIDTH ENHANCEMENT AND SINGLE SIDEBAND GENERATION

Under strong optical injection, the slave laser exhibits an enhanced modulation response [4]. Improved modulation efficiency, 3-dB bandwidth (BW) and resonance frequency may be achieved by optimizing the key parameters: the frequency detuning and injection power ratio between the master and the free running slave.

3-dB BW enhancement in recent works points to a requirement of above 16dB of injection ratio for up to 5-fold improvement upon the free running 3-dB BW. Recently, a 4-fold improvement to a 35.8GHz 3-dB bandwidth of a Vertical-cavity Surface-emitting Laser (VSCSEL) was realized at 20dBm of injected power [18]. In [17], a DFB DML was considered under several optimization conditions: a 5-fold BW increase was achieved at 18dB injection ratio and frequency detuning near the center of the locking range, while a resonance frequency of 72GHz was achieved at positive frequency detuning and injection ratio of 16dB. In [19], a simultaneous 2-fold expansion of VSCSEL 3-dB BW to 6.2GHz and linewidth reduction to 120kHz was attained by using OIL and an OFC at 9dB of injection ratio and positive frequency detuning. Most implementations require strong optical amplification and an optimized control of injection ratio and detuning frequency. Mutually injection-locked lasers have become an attractive research direction, achieving up to 2-fold bandwidth enhancement with simplified and cost-effective architectures [20].

Overcoming the power penalty caused by CD-induced carrier fading is critical in MMW systems since the effect scales proportionally to the fiber length and the square of the radio carrier frequency, and it is often based on OSSB modulation [3]. In the injection locked state of DFB lasers with strong injection and positive frequency detuning, the slave laser operates in two non-overlapping modes: an injection locked mode and a residual cavity mode with an ultra-narrow gain spectrum [21]. When the slave LD is RF modulated with frequency close to the difference between the injection locked frequency and cavity mode frequency, the lower sideband falls into the gain spectrum of the cavity mode, which results in its resonant amplification with respect to the upper sideband. Strong injection ratio, however, is achieved using optical amplifiers, which adds complexity and cost.

Recently, to overcome the bulky configuration and complexity of the OIL system, integrated lasers where the sideband amplification is based on the laser photoelectric characteristics were introduced for >20GHz MMW frequency applications in [22], [23]. Direct SSB modulation was achieved while maintaining the benefits of integrated lasers: lower power consumption, size reduction and immunity to nonlinear distortion.

4. CONCLUSIONS

In this paper, we discuss the benefits and limitations of OIL implementation in recently reported MMW ARoF systems. The outlined aspects of OIL implementation in such systems serve to identify current limitations and innovation paths towards multi-purpose use of OFC lines within the context of flexible and configurable optical fronthaul operation.

The overview outlines the most recent experimental demonstrations, illustrating the potential of various strategies for flexible OIL implementation, considering a wide range of transport frequencies and architectures. We consider the comparative potential of various OIL-based implementations for OFC generation and MMW tone selection, and identify the most promising approaches aimed at ARoF scenarios. We discuss recent advancements in DML modulation bandwidth enhancement towards the mitigation of impairments typical in cost-effective ARoF architectures. Finally, we address the recent developments towards the CD-induced carrier fading mitigation within the context of OSSB generation using OIL.

ACKNOWLEDGEMENTS

This work has received funding from the European Union's (EU) Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101073265 (EWOC). Z. Vujicic thanks the programme under grant agreement No. 872897 (EXPLOR). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the EU. The EU cannot be held responsible for them.

REFERENCES

- [1] A. Dogra *et al.*, "A Survey on Beyond 5G Network With the Advent of 6G: Architecture and Emerging Technologies," *IEEE Access*, vol. 9, pp. 67512–67547, 2021.
- [2] H. Ji *et al.*, "Spectral Efficiency Comparison Between Analog and Digital RoF for Mobile Fronthaul Transmission Link," *J. Light. Technol.*, vol. 38, no. 20, pp. 5617–5623, Oct. 2020.
- [3] W. Zhai *et al.*, "Multidimensional Optimization of a Radio-Over-Fiber Link," *IEEE Trans. Microw. Theory Tech.*, vol. 69, no. 1, pp. 210–221, Jan. 2021.
- [4] Z. Liu *et al.*, "Optical Injection Locking: From Principle to Applications," *J. Light. Technol.*, vol. 38, no. 1, pp. 43–59, Jan. 2020.
- [5] E. S. Lima *et al.*, "Integrated optical frequency comb for 5G NR Xhuals," *Sci. Rep.*, vol. 12, no. 1, Art. no. 1, Sep. 2022.
- [6] H.-H. Lu *et al.*, "Two-Way 5G NR Fiber-Wireless Systems Using Single-Carrier Optical Modulation for Downstream and Phase Modulation Scheme for Upstream," *J. Light. Technol.*, vol. 41, no. 6, pp. 1749–1758, Mar. 2023.
- [7] Q. Tareq *et al.*, "2 Gbit/s QPSK Wireless Transmission System with Injection-locked Quantum-dash Laser 28 GHz MMW Source at 1610 nm," in *2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, Munich, Germany: IEEE, Jun. 2021, pp. 1–1.
- [8] C.-Y. Lin *et al.*, "Millimeter-Wave Carrier Embedded Dual-Color Laser Diode for 5G MMW oF Link," *J. Light. Technol.*, vol. 35, no. 12, pp. 2409–2420, Jun. 2017.
- [9] E. Andrianopoulos *et al.*, "Optical Generation and Transmission of mmWave Signals in 5G ERA: Experimental Evaluation Paradigm," *IEEE Phot. Technol. Lett.*, vol. 34, no. 19, pp. 1011–1014, Oct. 2022.
- [10] L. Gonzalez-Guerrero *et al.*, "Injection Locking Properties of an Dual Laser Source for mm-Wave Communications," *J. Light. Technol.*, vol. 40, no. 20, pp. 6685–6692, Oct. 2022.
- [11] G.-W. Lu *et al.*, "Flexible generation of 28 Gbps PAM4 60 GHz/80 GHz radio over fiber signal by injection locking of direct multilevel modulated laser to spacing-tunable two-tone light," *Opt. Express*, vol. 26, no. 16, p. 20603, Aug. 2018.
- [12] C. Browning *et al.*, "Gain-Switched Optical Frequency Combs for Future Mobile Radio-Over-Fiber Millimeter-Wave Systems," *J. Light. Technol.*, vol. 36, no. 19, pp. 4602–4610, Oct. 2018.
- [13] A. Delmade *et al.*, "5G Millimeter-Wave Analog RoF System employing Optical Injection Locking and Direct Modulation of DFB Laser," in *Optical Fiber Communication Conference (OFC) 2022*, San Diego, California: Optica Publishing Group, 2022, p. W4C.7.
- [14] S. T. Ahmad *et al.*, "Active demultiplexer enabled mmW ARoF transmission of directly modulated 64-QAM UF-OFDM signals," *Opt. Lett.*, vol. 45, no. 18, p. 5246, Sep. 2020.
- [15] P. D. Lakshmijayasimha *et al.*, "Optical Linewidth Tolerant mmW Generation Employing a Dual-Stage Active Demultiplexer," *IEEE Photonics Technol. Lett.*, vol. 34, no. 9, pp. 451–454, May 2022.
- [16] P. D. Lakshmijayasimha *et al.*, "Tunable Mm-Wave A-RoF Transmission Scheme Employing an Optical Frequency Comb and Dual-Stage Active Demultiplexer," *J. Light. Technol.*, vol. 39, no. 24, pp. 7771–7780, Dec. 2021.
- [17] H.-K. Sung *et al.*, "Optical Properties and Modulation Characteristics of Ultra-Strong Injection-Locked Distributed Feedback Lasers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 13, no. 5, pp. 1215–1221, 2007.
- [18] M. E. Belkin *et al.*, "OIL-VCSEL-Based Microwave-Photonics Transceiver for a Millimeter-Wave Fronthaul," in *2021 IEEE 2nd International Conference on Signal, Control and Communication (SCC)*, Tunis, Tunisia: IEEE, Dec. 2021, pp. 330–333.
- [19] Y. Lu *et al.*, "Directly Modulated VCSELs With Frequency Comb Injection for Parallel Communications," *J. Light. Technol.*, vol. 39, no. 5, pp. 1348–1354, Mar. 2021.
- [20] S. Shao *et al.*, "Modulation Bandwidth Enhancement for Dual DFB Lasers Coupled with a High-Q Microring Resonator," in *2022 ACP*, Shenzhen, China: IEEE, Nov. 2022, pp. 1356–1358.
- [21] H.-K. Sung *et al.*, "Optical Single Sideband Modulation Using Strong Optical Injection-Locked Semiconductor Lasers," *IEEE Photonics Technol. Lett.*, vol. 19, no. 13, pp. 1005–1007, July 2007.
- [22] Y. Zhang *et al.*, "Experimental Demonstration of Single Sideband Modulation Utilizing Monolithic Integrated Injection Locked DFB Laser," *J. Light. Technol.*, vol. 38, no. 7, pp. 1809–1816, Apr. 2020.
- [23] X. Zhang *et al.*, "Integrated Direct Single Sideband Modulation Utilizing Sideband Amplification Injection Locking Effect Based on Multi-Section Mutual Injection DFB Laser," *J. Light. Technol.*, vol. 39, no. 6, pp. 1645–1652, Mar. 2021.